TRANSIENT SIMULATION OF LIQUID ROCKET ENGINES: 
A STEP TOWARDS A MORE EDUCATED PROPELLANT CHOICE BETWEEN 
KEROSENE AND METHANE

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ABSTRACT

It is renowned that transient simulation is a powerful tool which reveals fundamental characteristics of any liquid engine. Using the program TLR-Sim (Transient Liquid Rocket Engine Simulator), whose development has recently begun, both LOX/Kerosene and LOX/Methane engine components have been closer examined whilst seeking for a clear indication of advantages associated with the use of one or the other in a number of potential engine applications. Results of the performed simulations are presented and commented.

The program TLR-Sim and its development are shortly presented. A short summary of the program structure and main characteristics precedes the detailed engine analysis and comparison. A brief conclusion will follow, outlining both the main results of the inspection and a future roadmap for a subsequent program evolution.

NOMENCLATURE

\[
\begin{align*}
\rho & \quad \text{density} & \text{kg/m}^3 \\
\omega & \quad \text{Frequency} & \text{Hz} \\
\zeta & \quad \text{Friction factor} & \text{1/m}^4
\end{align*}
\]

1. INTRODUCTION

In the frame of an internal study at DLR, the program TLR-Sim is under development with the goal of performing transient simulations of liquid rocket engine components.

In the attempt of finding the “best” alternative to the cryogenic propellant couple LOX/LH2, studies have been concentrated on comparisons between numerous propellant couples. Amongst the most targeted are LOX/Kerosene, for the latter's storability characteristics, and LOX/Methane, for possible lower acquisition costs, potentially higher achievable specific impulse, lower pressure drop in cooling channels, superior cooling properties and higher coking limits [2].

Engine nominal operational point comparisons have already been examined and presented by the DLR Space Launcher Systems Analysis (SART) department. These have led to the conclusion that although the increased motor mass, booster size and hence drag, a reusable methane engine could provide a competitive solution to the extensively studied kerosene engines, with the premise of further studies.

The purpose of the study underway is to fill one of the gaps existing in previous studies, namely the examination and comparison of the transient behaviours of the propellants themselves under specific conditions.

2. PROGRAM STRUCTURE

The program TLR-Sim possesses a highly modular structure in order to assure as high a degree of flexibility as possible. The general program structure is illustrated in the scheme in Figure 1.
3. DUCT SIMULATION METHODS

Within TLR-Sim, numerical routines for the simulation of a number of different components have already been implemented. Being, however, the focus of this paper fluid flow through pipe lines, this section concentrates only on the simulation methods existing within TLR-Sim for the computation of duct flows.

3.1 Ducts

All components falling under this category, that is, rigid and flexible pipes can be simulated by applying a number of different techniques. These techniques may be classified according to the detail to which they examine the flow. General ODEs (ordinary differential equations) can be used to compute pressure changes, mass flow variations etc. (see Section 5) More detailed schemes allow, not only the computation of the flow properties, but also the evaluation of its structure. Two major techniques in the category of more detailed methods are the following:

- Method of characteristics (MOC)
- Riemann Solvers (RS)

The Method of Characteristics has a wide range of applications, thus an equally vast class of possible constructions. One can choose, for example, between explicit and implicit solving methods. A literature survey has revealed that implicit methods, when applied to sharp transients, can lead to initial errors which are carried through the entire calculation and may lead to questionable results. The choice thus falls on the explicit solving routines. Further decisions, coherent with the problem at hand, must be made in the future.

Riemann Solvers solve for the Riemann problem (RP) which is none other than a special case of the Initial Value Problem (IVP). Riemann solvers can be adopted to solve a local RP at any position along a duct. The solution to the RP is then used to solve for the Euler equations with or without additional source terms.

Although being somewhat more complex, the use of Riemann solvers can be implemented in the solving of problems where the MOC is not suitable. As will be described in Section 6, the study here presented has made use of the Riemann solvers to solve the Navier-Stokes Equations.

4. KEROSENE – METHANE COMPARISON

4.1 Analysis Background

In previous studies conducted in the Launcher’s Systems Analysis department of the German Aerospace Centre, DLR, two engines in the RD-180 class have been hypothesised to compare the performance of methane and kerosene under nominal engine operation. The paper at hand has taken these engines as its starting point [2].

Table 1 summarises the tank conditions for each of the methane and kerosene RD-180 class engines.

<table>
<thead>
<tr>
<th>Table 1.Propellant Tank Parameters</th>
<th>Methane</th>
<th>Kerosene – RP 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Pressure</td>
<td>bar</td>
<td>3</td>
</tr>
<tr>
<td>Tank Temperature</td>
<td>K</td>
<td>110</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>427</td>
</tr>
</tbody>
</table>
4.2 Analysis Breakdown

The study here presented is based on a two-fold analysis. The first is based on non-linear ODEs (ordinary differential equations) describing the evolution of pressure and mass flow along a duct and is performed with an ODE integrating tool. The second aspect of the analysis is a more detailed one consisting in the implementation of the Navier-Stokes equations to evaluate the potential differences between kerosene and methane.

In the following sections each of the above-mentioned assessments is introduced, the underlying model is highlighted and the out-coming major results are presented.

4.3 Propellant Properties

It should be noted that Jet A1 data has been used due to its easy availability. Difference between RP 1 and Jet A1 due exist but for present purposes are of minor importance [4], [6].

Figures 2 and 3 illustrate the viscosity of methane and kerosene as functions of temperature and pressure. The plots show that, within the pressure and temperature range of interest, methane viscosity values can be an order of magnitude smaller than those of kerosene. Similar curves depicting methane and kerosene density show in this case the ratio is only two-fold.

5. ODE ANALYSIS

5.1 Introduction

The ODE analysis has been performed with a program widely used at DLR for the simulation control laws such as those existing in aviation flight control systems. The tool has the capability of integrating ordinary differential equations and allows for feedback loops.

5.2 ODE Equations

The fluid parameters, pressure and mass flow, characterising the fluid flow though a duct can be expressed according to the following ODEs [3]:

\[ \frac{dm_f}{dt} = \frac{F_f}{l_f} \left[ p_{in_f} - p_{out_f} - \frac{1}{\rho_f} \xi_f \dot{m}^2_{out_f} \right] \]  
\[ \frac{dp_{in_f}}{dt} = \frac{a_f}{V_f} \left[ \dot{m}_{in_f} - \dot{m}_{out_f} \right] \]

where the subscript \( f \) stands for \( \{K, M\} \) for kerosene and methane respectively.

The friction factor \( \xi \) is a function of the Reynolds number, and for turbulent flows, i.e. \( \text{Re} \geq 2300 \) is defined as:

\[ \xi_f = 0.11 \left( \frac{h_f}{\text{Re}_f} + \frac{68}{\sqrt[4]{\frac{l_f}{d_f}} \frac{1}{2F_f^2} + \frac{\xi_G}{2F_f}} \right) \]

where \( \frac{h_f}{d_f} \).
5.3 ODE Model

The model used in the ODE analysis is aimed at reproducing, in more simple terms, the start sequence of a rocket engine employing a burst disk and includes a tank directly connected with a duct. Bends and area-variations have not been taken into account. Acceleration effects stemming from the launcher system have also been neglected. In the model the burst disk is assumed to be located just before the first duct section. The duct is broken down into sections each having an inlet pressure, an outlet pressure and inlet and outlet mass flows. Figure 4 illustrates the model used.

Each duct section is of equal length and is user defined according to:

$$f_{max,j} \leq \frac{2\pi a_f}{\sigma_{max_j} n} \quad (4)$$

where $\sigma_{max}$ is the maximum frequency that is to be examined.

Under the spectrum of the ODE analysis, three models have been used. Each model differs in the length of its duct sections. Table 2 summarises the main details of each model configuration.

Table 2. Model Configurations and Corresponding Frequencies

<table>
<thead>
<tr>
<th>Model</th>
<th>Section Length [m]</th>
<th>$\sigma_{max}$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>1.0</td>
<td>$\leq$ 900</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.2</td>
<td>$\leq$ 4200</td>
</tr>
<tr>
<td>Model 3</td>
<td>0.4</td>
<td>$\leq$ 2100</td>
</tr>
</tbody>
</table>

5.4 ODE Results

The graphs shown below have been obtained by implementing the three different models described above. Although each model differs from the others in the length of its duct sections, the total duct length examined has been kept. Each graph depicts normalised pressure, i.e. the pressure in the duct normalised to the pressure in the respective tanks (3 bar for methane and 2 bar for kerosene), against time in seconds. In addition to centre of the duct where the evolution of pressure is shown, two further locations have been plotted for each model. These are the entrance and exit locations of the duct. The initial pressure within the duct has been assumed to be one bar lower than pressure existing within the tank (corresponding to a normalised pressure of 0.5 for kerosene and approximately 0.67 for methane).
6. 1-DIMENSIONAL NAVIER-STOKES ANALYSIS

6.1 Introduction

The one-dimensional Navier-Stokes analysis has been built on the Euler equations with the addition of a series of sources terms deemed as important for fluid flow in ducts. These source terms include area variations as well as viscous and heat contributions.

6.2 Navier-Stokes Equations and Riemann Solvers

The Navier-Stokes equations in conservative form are as follows:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} &= \frac{\partial \mathcal{F}(\tilde{\mathcal{U}})}{\partial x} + \mathcal{S}_1 + \mathcal{S}_2 \\
\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u^2}{\partial x} + \frac{\partial (\rho e)}{\partial x} &= \frac{\partial \mathcal{E}}{\partial x} + \mathcal{S}_1 + \mathcal{S}_2
\end{align*}
\]

where \( \mathcal{S}_1 \) and \( \mathcal{S}_2 \) are source terms accounting for area-variation and viscous and heat effects and which upgrade the one-dimensional Euler equations to the one-dimensional Navier-Stokes equations with area-variations.
By adopting the WAF (Weight Averaged Flux) method proposed by Toro [5], and using an exact Riemann solver and an appropriate flux limiter, the Riemann problem can be solved for each \( \bar{U}(i, i + 1) \), along the duct. The result to the local Riemann problem in conjunction with a conventional TVD (Total Variation Diminishing) scheme can then be implemented to obtain the result to the Euler equations for all positions, \( i \) along the duct for a given time, \( n \). Subsequently the source term effects are added to obtain the solution to the Navier-Stokes equations.

6.3 Results

Figure 8, as Figures 5 through 7 for the ODE analysis, depicts normalised pressure vs. time. The results correspond to a shock-tube problem set up to have the same starting conditions as the ODE analysis. The purpose of this evaluation is to provide an indirect comparison to the ODE results for a somewhat different problem and thus validate the general characteristics shown by kerosene and methane.

7. CONCLUSIONS AND OUTLOOK

The two-fold analysis here presented has highlighted three fundamental aspects. Firstly: the dynamic behaviours of kerosene and methane have been shown to possess substantial differences, thus underlying the importance of a transient analysis. Secondly: the ODE and Navier-Stokes analyses have led to coherent results though applied to different test cases. This shows that the transient analysis can be performed with tools having different focuses, thus allowing the choice of the best tool to suit the problem at hand and thus holding a considerable advantage. Thirdly: a more advanced transient simulation which includes additional engine components and examines their interactions for a range of operating conditions represents an advantage in engine analysis and should be pursued.

Thus, further examinations and program developments are underway not only for different ambient conditions but for more complex models, comprehending other LRE components such as valves and combustion devices.

8. REFERENCES